§11. Gyrokinetic Turbulence Simulations of High-beta Tokamak and Helical Plasmas with Full-kinetic and Hybrid Models

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Electromagnetic simulation codes for studying micro-turbulence in magnetically confined plasmas, such as GKV+/EM solving the gyrokinetic equations for ions and electrons and GKV+/EMH solving the hybrid model of gyrokinetic ion and fluid electron equations, are newly developed. These codes are applied to the linear and nonlinear analyses of micro-instabilities of finite beta plasmas in the Cyclone base case tokamak and in a model configuration of standard LHD [1)].

Accuracy of the hybrid model is confirmed through comparison with linear and nonlinear simulation results for the tokamak and the LHD plasmas obtained by the full gyrokinetic code. The comparison in the linear analysis confirms good agreement in the growth rates and real frequencies of KBMs in high-beta regime. In nonlinear simulations the hybrid code can run with about four times faster speed than that of the full gyrokinetic code. The hybrid code is especially useful for nonlinear analysis of LHD for which full gyrokinetic simulation is difficult because of large computational cost.

The nonlinear simulation of KBM turbulence in the CBC with $\beta = 2\%$ and $\eta_e = 0$ shows that the ion heat (particle) transport coefficient given by electrostatic perturbations is about 0.6 (0.5) $v_{Ti}\rho_i^2/L_n$. The magnetic perturbation of KBM turbulence has small pinch effects on the ion heat and particle transport, which is in contrast with Rechester-Rosenbluth model. The electron heat flux is about 0.4 $T_i v_{Ti}\rho_i^2/L_n^2$ (-0.3 $T_i v_{Ti}\rho_i^2/L_n^2$) for $\eta_e = 0.2$ ($\eta_e = 0$). The analysis of beta scaling of these fluxes and a comparison between the kinetic simulation results and our previous fluid simulation results will be made in our future work. Turbulent fluctuation of KBM satisfies the entropy balance equation, and the entropy (or free energy) is transferred from ions to electrons.

Although it has been shown that the zonal flow produced by KBM is weak compared to ITG with the adiabatic electron, it is valuable to study the production of zonal structure in KBM turbulence. By using the entropy balance relation it is shown that the entropy transfer to the zonal component from magnetic (electrostatic) nonlinearity is positive (negative). It is noticed that the magnetic (electrostatic) nonlinearity corresponds to the Maxwell (Reynolds) stress in the fluid limit. This zonal structure production is in contrast with the production (reduction) of zonal flow by the Reynolds (Maxwell) stress in two-fluid simulations [2)].

Linear analysis of KBM in the model configuration of standard LHD plasmas by means of the full kinetic code shows that the ITG mode is stabilized around $\beta =$ 0.8% and the critical value of KBM onset is about $\beta =$ 1.5% for $\eta_i = 3$, $\eta_e = 0$ and $\hat{s} = -0.85$. When $\eta_e = 3$, the growth rate of ITG is suppressed with beta but it is not stabilized completely and KBM appears in $\beta > 1\%$. One of the significant feature of KBM in the standard LHD is that the most unstable mode has a finite radial wavenumber. This is in contrast to ITG in the LHD and micro-instabilities in tokamaks, where the most unstable mode has vanishing radial wavenumber, which is then set by the magnetic shear length scale.

The first nonlinear simulation of turbulence in the finite beta LHD plasma is demonstrated, and the early stage of nonlinear saturation of KBM with $\beta = 2\%$, $\eta_i = 3$ and $\eta_e = 0$ is obtained. The magnetic perturbation of KBM causes small ion heat and particle pinches. After the KBM growth is saturated, small k_y modes grow and the system does not reach a steady state. These small k_y modes are linearly unstable, and the zonal flow is too weak to regulate these modes. This is a possible explanation of the difficulty in finding a steady state in the standard LHD with the magnetic hill component in the magnetic drift term. In contrast the ITG has stable region in small $k_y\rho_i$ and also produces strong zonal flow. Other possible explanations of the difficulty are the lack of numerical resolution and the model configuration used in the present study. Electromagnetic gyrokinetic simulations of LHD plasmas with higher resolution and with a realistic magnetic configuration remain in our future work.

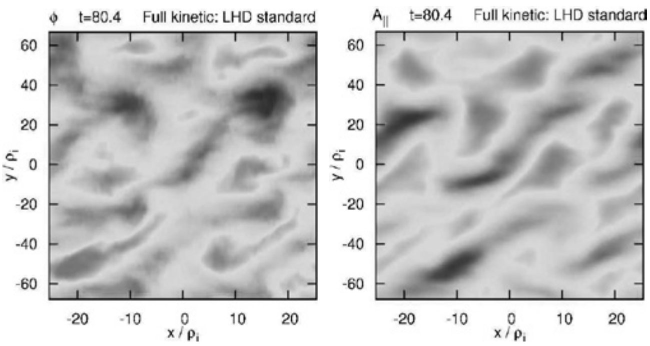

Fig. 1: Color contours of electrostatic potential ϕ and parallel component of vector potential $A_{\parallel}$ on $z = 0$ at $t = 80.4 L_n/v_{Ti}$.

1) Ishizawa, A., Maeyama, S., Watanabe, T.-H., Sugama, H., and Nakajima, N., Nuclear Fusion **53**, (2013) 053007.

2) Ishizawa, A. and Nakajima, N., Nuclear Fusion **47**, (2007) 1540.